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Using GIS and remote sensing to monitor industrial impacts to archaeological sites in the Athabasca Oil Sands of Alberta

William T. D. Wadsworth[a]*, Ave Dersch[b], Robin J. Woywitka[c], and Kisha Supernant[a]

[a] Institute of Prairie and Indigenous Archaeology, Department of Anthropology, University of Alberta, Edmonton, Alberta, Canada, T6G 2H4

[b] Moccasin Flower Consulting Inc., Slave Lake, Alberta, Canada, T0G 2A4

[c] Department of Physical Sciences, MacEwan University, 5-138S City Centre, Edmonton, Alberta, Canada, T5J 4S2

* corresponding author: wwadswor@ualberta.ca

ABSTRACT

The Athabasca Oil Sands (AOS) region of Alberta has one of the densest accumulations of known archaeological sites, and possibly the most archaeological sites at risk, in the country. Expanding industrial development has been a characteristic of this region for decades, and as a result, abundant archaeological work has been done and regulatory requirements put in place to mitigate site disturbance. Until recently, there has been little quantitative evidence to assess human impact on archaeological resources in the region. The goal of this paper is to raise awareness of the critical need to incorporate new archaeological remote sensing strategies to improve site monitoring approaches. We present methods and results from our GIS-based analysis that seeks to locate and partially characterize impacted sites. We argue that combining publicly accessible remote sensing products with geospatial archaeological site information allows for better documenting and monitoring of industry impacts in the AOS. We show that 43% of all sites sampled (n=1943) are disturbed. Of these sites, 160 were potentially affected by *Historical Resources Act* non-compliant impacts (including five HRV 1 sites). We contextualize our results within current systemic challenges and we recommend the incorporation of community monitoring programs to ground-truth similar GIS analyses and increase our ability to effectively monitor industrial impacts to archaeological sites.

KEYWORDS

Athabasca Oil Sands, monitoring, disturbance, GIS, remote sensing, site boundaries, northern Alberta, Indigenous archaeology, impact, Boreal Forest

1. Introduction

The impact of widespread and expanding resource extraction on archaeological resources has been known for decades (Byrne 1976:1-2; Ronaghan 2017a). In Alberta, the *Historical Resources Act* (*HRA*; Queen's Printer 2021) was passed in 1973 to help prevent and mitigate industrial impacts to archaeological and other heritage sites and landscapes. Since that time, an archeological regulatory framework has been developed from the *HRA* that is managed by the Archaeological Survey of Alberta (ASA; Province of Alberta 2013). Work conducted under this framework has led to the recording of tens of thousands of archaeological sites and the composition of thousands of reports (Bereziuk et al., 2021). This constitutes the bulk of recorded archaeological knowledge for Alberta.

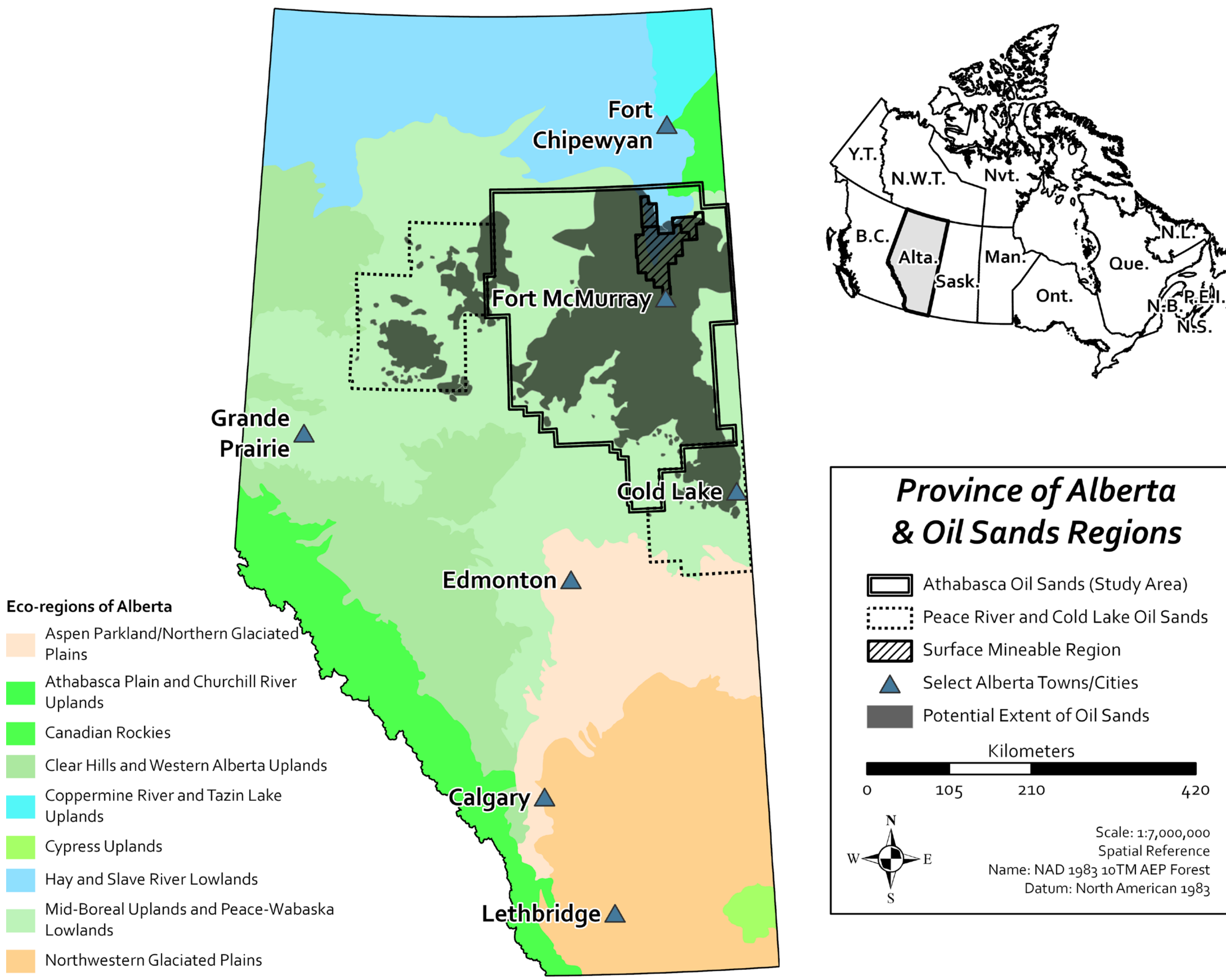


Figure 1. Map of the study areas within the province of Alberta, and potential oil sands deposits. Map also shows key population centers. Potential extent of oil sands is a layer on ArcGIS Online published by Ted Auch (The FracTracker Alliance) and available here: https://www.arcgis.com/home/item.html?id=4b7863a60c8844a3824a7d58f0238a30.

Although the regulatory system is designed to prevent or mitigate impacts to archaeological sites (measures taken to limit risk to interpretation potential), significant loss of scientific and cultural knowledge remains an issue. Due to the variety of impacts that endanger archaeological sites, many cannot be preserved and those that are excavated cannot be replaced. From a scientific perspective, this means that insights from archaeological work are limited by theoretical and methodological capabilities available at the time of study. From a cultural perspective, the potential knowledge encapsulated in archaeological sites is lost from the near-total absence of Indigenous perspectives in *HRA*-triggered studies.

As more sites are impacted by development through time, cumulative knowledge loss grows, and this erasure is particularly evident in the Athabasca Oil Sands (AOS) region of Alberta (Figure 1). Home to many Indigenous communities (including First Nations and Métis), the region also contains one of the densest accumulations of archaeological sites known in Canada (Ronaghan 2017b). These culturally and archaeologically significant places are under threat from expanding industrial activities. Despite unparalleled research and knowledge potential, many sites (with and without government protection) are damaged or removed by industry, their material culture lost, and possible contributions to modern Indigenous communities never fully realized.

There have been few attempts to quantify cumulative effects on archaeological sites as a result of industrial developments (Ronaghan 2017a). We address this knowledge gap by reviewing the Government of Alberta's current approach to monitoring archaeological sites in northeastern Alberta and discuss some of its challenges. We describe the methods and results of a geographic information system (GIS) project that utilized publicly available satellite-derived remote sensing datasets to quantify and map archaeological sites that have been impacted by industrial development within the AOS region. It is our intent to provide an accurate assessment or 'snapshot' of the extent and severity of industrial impacts to AOS archaeological sites, which can be used to inform future site monitoring practices. Moreover, we present a replicable methodology that can be applied to other regions in Alberta and elsewhere in North America. Finally, we argue that, with government support, combining simple satellite remote sensing approaches with enhanced Indigenous community-based ground-truthing efforts could ultimately provide better protection for many endangered sites. Cumulative effects analyses like our study are also a necessary first step for Indigenous communities who wish to begin exercising their inherent right to active roles in the co-management and protection of archaeological sites, as per the United Nations Declaration on the Rights of Indigenous Peoples - Article 11 (2007).

2. Study area

The archaeological record of northeastern Alberta spans over 10,000 years of human history (Ives 1993; Ronaghan 2017b). Over this time, the region has undergone massive environmental changes, which has also resulted in changing cultural systems and lifeways (Ives 1993; Clarke et al. 2017; Saxberg and Robertson 2017; Younie et al. 2017; Woywitka 2018; Woywitka and Froese 2019; Norris et al. 2021). Descending from this long history, Dene Sųłiné, Cree, and Métis peoples call the AOS region their home, and their relationships with the Boreal Forest landscape nourishes them physically, socially, and culturally (e.g., Athabasca Chipewyan First Nation 2003; Chipewyan Prairie Dené First Nation 2007). For many Indigneous groups in the AOS, the pre-development baseline is defined as the 1960s, a time when settlers had shifted to new forms of resource extraction focused on forestry and oil sands mining (Longley 2015; Nenzén et al. 2019). These industries continue to impact Indigenous communities today by changing the environment through open pit and *in situ* oil sands development, forestry clear cutting, and construction of transmission lines and pipelines. As a result of at least 10,000 years of pre-contact history and a relatively early necessity for industry-driven archaeology, over 3400 archaeological sites have been located in the AOS region thus far (Ronaghan 2017b:6). Since 1973, archaeologists have worked to protect this significant record from being erased by industry expansion.

The rich deposits of bitumen in the Athabasca Oil Sands region led to an explosion of industry in the mid-20th century, helping Alberta to become an economic powerhouse in Canada (Longley 2015). Hand-in-hand with the development of the oil sands was the need to deforest/clear the area for oil sands mining to begin. To date, these mining operations have removed 895 square kilometres of Boreal Forest (Nenzén et al. 2019) with the remaining 4,800 square kilometres set aside as the surface-mineable area for oil sands development to proceed in the future. Far exceeding the footprint of the oil sands, forestry harvest operations in Alberta's Boreal Forest natural eco-region have removed 2.71% of forest or 10,589.76 square kilometres (Schieck et al. 2014). Although different aspects of both oil sands mining and forestry have varying levels of impact to archaeological sites, each have the potential to damage a site and remove scientific and cultural information from the area (see CRICS scale in Gibson 2019 [2005]). Due to the potentially heavy impacts associated with these industries, the province of Alberta mandates that mining companies restore the Boreal Forest land they use to "equivalent land capability" (Nenzén et al. 2019:40). In a similar vein, academic and government scientists have agreed upon thresholds that stimulate monitoring and prevent industry impacts to wildlife and their environments (e.g., caribou; Government of Alberta 2011). No such quantitative thresholds exist for the non-renewable archaeological/heritage resources in Alberta, representing a significant uphill challenge for the Archaeological Survey of Alberta and the cultural resource management (CRM) industry. While information about these resources can be learned from excavation, the archaeological heritage cannot be restored once removed from the ground in the way that forest can be regrown.

3. Monitoring site impacts in Alberta

3.1 HRV and site monitoring

Sites in Alberta are ranked according to the Historic Resource Value (HRV) system (Table 1). This system is part of the broader archaeological regulatory framework and is designed to prioritize sites relative to their degree of significance or interpretive potential as determined by archaeologists. Sites with ratings of 1-4 are afforded different levels of protection; HRV 1 sites are protected under provincial designations, and HRV 3 and HRV 4 sites require avoidance or further study. HRV 5 ratings are applied to high potential lands that surround known sites and other areas of archae-

Table 1. Definition of Historic Resource Value. HRV 1-5 taken from Alberta Culture and Status of Women's (2021) "Listing of Historic Resources: Instructions for use." HRV 0 does not have a formal definition but is understood as the below.

Historic Resource Value (HRV)	Definition / Description
1	Contains a World Heritage Site or site designated under the *HRA* as a Provincial Historic Resource
2	Deactivated (formerly used to designate a Registered Historic Resource)
3	Contains a significant historic resource that will likely require avoidance
4	Contains a historic resource that may require avoidance
5	Land with high potential to contain a historic resource
0	Insignificant or cleared

ological sensitivity. HRV 5 ratings are not applied directly to sites but are used in other components of the regulatory system (e.g., the Listing of Historic Resources, which is an online spatial tool used in part to trigger reviews of industry footprints). Although CRM professionals and other archaeologists recommend HRVs, they are subject to ratification by the Government of Alberta. These ratified HRVs are recorded in the ASA site database and the Listing of Historic Resources (biannually released to the public; Alberta Culture and Status of Women 2021).

3.2 HRV and CRM fieldwork

When the ASA receives a proposal for a development activity that could damage known historic resources of significant interpretive value (i.e., HRV 1-4), known high potential land or land of unknown potential, it can trigger a Historic Resources Impact Assessment (HRIA). An HRIA is a field study conducted by CRM archaeologists (at the expense of the proponent) to investigate whether or not the proposed development will impact significant historic resources. These surveys include re-appraisal of known HRV 1-4 sites in relation to the proposed development and assessment of high potential areas that could yield new sites. If no sites are found and the survey is considered adequate by the ASA, no site-specific conditions are attached to the *HRA* approval. If sites occur within the project boundaries, different conditions may be placed on the development project by the Government of Alberta following the completion of an HRIA:

1) The development may be approved to impact all sites recorded. This occurs when work conducted during the HRIA only identifies new sites with HRV 0 ratings and/or re-assessment of previously significant sites warrant downgrading to HRV 0;

2) The development may be approved to impact all HRV 0 sites, but avoidance or further study is required for HRV 1-4 sites. These further studies often fall into the category of Historic Resources Impact Mitigation (HRIM) studies.

For significant sites that cannot be avoided, approval to impact is not issued until adequate HRIM study has taken place. How adequate HRIM study is achieved varies according to site type, project lineage, and region, but the end result is the same: the data and artifact assemblages collected during HRIM studies are considered sufficient by the regulator to offset physical impacts to the site. That is, a portion of the resource is recovered and archived as permit reports, excavation plans, artifact catalogues, radiocarbon dates, and other analyses along with interpretations. Usually this results in downgrading the site to HRV 0. In some cases, impacts to disturbed areas or portions of HRV 1-4 sites that have been subject to previous HRIM studies may also be approved. In this case the site retains a non-HRV 0 rating and (problematically) the boundaries are not adjusted to remove the disturbed or HRIM-studied portions. The intent of this practice is to convey a sense of the site's original location and distribution of resources, however, this also makes monitoring impacts to archaeological resources difficult for government regulators.

3.3 Understanding site disturbance

Prior to construction, the ASA requires submission of final development plans in order to dictate archaeological activity in a region. A focus of this study is the concept of a "trespass", or *HRA* non-compliant impact, which is when a development impacts an archaeological site without government approval. The ASA discovers trespasses through three different mediums: site revisits, company self-report, and review of development "as-built" plans. In the case of site revisits, consulting archaeologists may be required to revisit HRV 1-4 sites as part of the HRIA process. Site revisits may also occur in academic or Indigenous community driven studies, but this happens less often. Company self-reporting occurs when a development accidentally disturbs an archaeological site. Although they are legally obligated to report the disturbance to the ASA, according to the *HRA*, this entirely relies on good will of the companies, and it is possible that many trespasses of this type go unreported. Once a development is finished, proponents can file "as built" plans (which are provided if final development plans were not available prior) that include spatial data of the final development footprints. Using these footprints, archaeology regulators can identify unsanctioned impacts to archaeological sites. Prior to 2020, "as built" plans were not always submitted to the ASA rendering this a useful but opportunistic method at detecting trespasses. If the Government of Alberta believes a trespass has occurred or could occur, they have the legislative authority to prevent the impact to these resources or seek monetary penalty for the loss (see Articles 34, 49 and 52 of the *Historical Resources Act*). Given that the system for monitoring trespasses in Alberta is *ad hoc* and reliant on self-report or serendipity, much fewer violations are prosecuted than are committed or reported. While no number for these has been published, similar issues in penalizing individuals / corporations for the disturbance of archaeological sites has been noted in other regions (e.g., the United States and England; Shelbourn 2007:273-275), and site-specific observations from Alberta have noted the ineffectiveness of heritage legislation to deter disturbance (see Brink 2014:186 for a case of vandalism and looting).These cases suggest that, without a way to track disturbances accurately and with reasonable efficiency to prosecute the individuals responsible, the ability of heritage legislation to protect archaeological sites is much less effective than originally hoped.

With modern advances, shortcomings in this monitoring process can be evaluated, and potential site monitoring solutions provided. Due to recent developments in open-source data availability and increased calls for industry accountability across a multitude of disciplines, satellite remote sensing products (i.e., Alberta Biodiversity Monitoring Institute's [ABMI] Human Footprint Inventory) have been made more publicly accessible. This has made it possible to track land disturbances across large areas at high temporal and spatial resolutions. The ability of archaeologists to audit industrial activities relative to heritage sites has increased because of these technological improvements. To date, the bulk of remote sensing monitoring research for archaeological sites has been undertaken in Europe (e.g., Stewart et al. 2018; Angiuli et al. 2020; Rayne et al. 2020; Fisher et al. 2021; Tapete et al. 2021), although Canadian studies have also taken place (Hodgetts and Eastaugh 2017; O'Rourke 2017; Pennanen et al. 2017; O'Rourke 2018). In this paper, we present a method that utilizes anthropogenic disturbance data to monitor impacts to archaeological resources in a new setting: the Boreal Forest of Alberta.

4. Methods

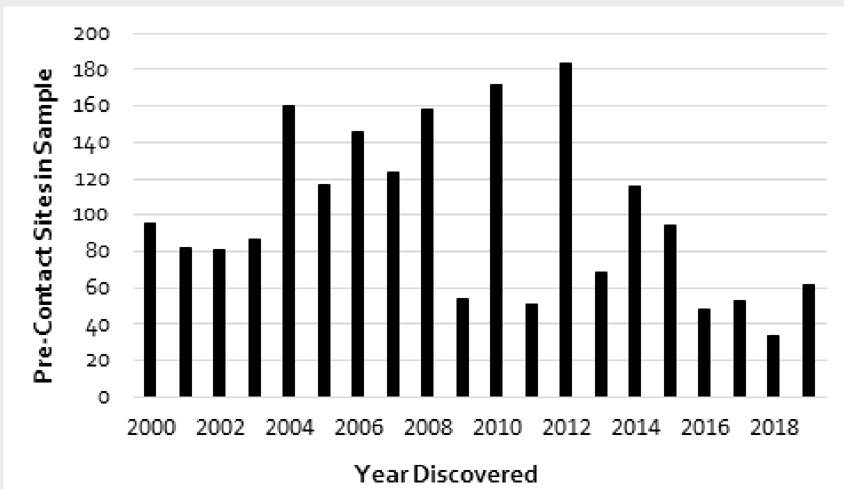
4.1 Archaeological sites

In January 2022, site polygons were obtained from the Archaeological Survey of Alberta for the Athabasca Oil Sands (Figure 1), and summary statistics were calculated (Table 2). Woywitka and Beaudoin (2009) have shown that sites recorded in the Alberta database prior to the widespread adoption of handheld Global Positioning System (GPS) devices could be subject to mapping errors of hundreds of metres. Due to this potential source of error, we have limited our analysis to sites recorded after 2000, when selective availability of GPS data was discontinued by the United States government and the bulk of archaeological site data in Alberta was recorded using handheld units. Although spatial accuracy is not reported with site polygons, a 2009 study found that handheld GPS in dense southern forest had positional accuracy of ±12-40 metres (Danskin et al. 2009). An updated study showed that modern GPS technology is more capable at handling forest canopy, with a recreational GPS watch being able to obtain (on average) ±12.21 metres, and handheld / survey-grade equipment having much higher accuracy (Lee et al. 2020). Regardless of the product used, on average, the size of pre-contact sites (see Table 2) suggests that although their in-field boundaries might not match perfectly with those in the site database, most significant impacts to sites should be caught by an impact model (or at least not missed in their entirety).

Upon examination of the site counts within archaeological site classes (e.g., pre-contact, historic, multi-component), we decided to limit our analysis to pre-contact archaeological sites for several reasons. Firstly, it is possible that clearings and structures related to historic and contemporary sites may be the reason an area appears in the AMBI disturbance footprints (e.g., early or pre-1950s oil sands exploration/development or early agriculture). This would artificially inflate the number of sites classified as disturbed in our analysis. Pre-contact sites are defined as those that have "Prehistoric" listed as the first or only site class in the ASA database. This means some sites that have historic and pre-contact elements may be included in the site sample. However, only 50 multi-component sites occur in the dataset, and we assume their influence on our results is minimal. As a result of our restrictions based on year of site discovery and site class, the total number of sites used in this sample is 1,984, and Table 2 summarizes the sample characteristics.

Table 2. Summary table of pre-contact sites (2000-2019) in the Athabasca Oil Sands region that are used in the present analysis. This table only represents sites with described conditions as of January, 2022.

Total number of sites			**1,984**
Average site size (m²)			**3,859**
Historic Resource Value	HRV 4 (#)		737
	HRV 0 (#)		1224
	HRV 3 (#)		4
	HRV 1 (#)		19
Site type (total # and % of sample)	Isolated find	424	21.36%
	Scatter <10	632	31.84%
	Scatter >10	357	17.98%
	Campsite	158	7.96%
	Workshop	151	7.61%
	Scatter >10, workshop	91	4.58%
	Multiple site types	172	8.66%



4.2 Anthropogenic disturbance data

ABMI's (2021) Wall-to-Wall Human footprint dataset was selected for this impact analysis. Every year, ABMI classifies satellite imagery to interpret anthropogenic disturbances on the land and sorts them into categories (e.g., mine sites, forestry cut blocks, and pipelines). ABMI's human footprint dataset uses primarily SPOT-6 (Satellite Pour l'Observation de la Terre) commercial data to create their classified satellite products. The dataset is combined with historical information and already-classified changes, so that although the predominant use of SPOT-6 data means that the majority of the dataset has a high spatial resolution of 2.5 metres, in reality, different dataset features have different spatial resolutions (see ABMI 2021:57). SPOT's high resolution is substantially better than other publicly available satellite data (e.g., Landsat) making this dataset well-suited for capturing and analyzing human disturbance footprints. Each year newly acquired data are classified by the ABMI team and added to the cumulative human footprint dataset before ABMI releases the datasets publicly on their website. As a result, researchers need only download the most recent dataset to model both present and past conditions. For this study, we used ABMI's (2021) "Human Footprint Inventory Enhanced for Oil Sands Monitoring Region 2019" dataset, as it also included additional information about the origin of each human footprint (i.e., industry and year) and its present state (according to Normalized Difference Vegetation Index [NDVI], day/night band, and radiance). We removed disturbance categories that occur in agricultural areas and categories that hold limited likelihood to result in ground disturbance deep enough to impact buried archaeological sites. Removed categories include: "crop," "cultivation, abandoned," "rough pasture," "fruits/veg," "conventional seismic," and "low impact seismic". The majority of the remaining impacts would require *HRA* approval prior to construction.

It is important to note that ABMI industry footprints are not the same as areas reported to be disturbed by companies (such as in "as built" plans). Instead, footprints include all areas (claimed or unclaimed) that were assigned as disturbed using a pixel-based classification algorithm iteratively developed by ABMI (2021). Mapping archaeological sites over these classified areas describes which sites have the potential to be impacted, but further ground reconnaissance would be required to determine the extent of this impact. These footprints could be far more telling than "as built" plans as there are fewer data availability barriers.

4.3 Data analysis

Site discovery and impact dates were extracted from the ASA geospatial site database and ABMI disturbance dataset. The ABMI dataset provides only the year of impact, so our analysis uses that as the minimum temporal unit. We added a field to the archaeological site geospatial data called "Initial Discovery Year" by extracting the year digits from the first associated archaeological permit. We then used a series of spatial joins in ArcMap 10.5 to determine the following for each archaeological site in the AOS (Figures 2 and 3):

1) Areas where industrial impacts intersected the site boundary;

2) The number of times the site has been impacted;

3) The date of the first site impact;

4) The date of the most recent site impact; and

5) The types of industries attributed to site impact according to the ABMI footprint data.

We also used the 'intersect' tool to extract the area overlap between impacted footprints and site boundaries, these were then divided by the overall site size (calculated from boundaries) to get an approximate percentage for how much of the site had been disturbed. From these attributes we quantified impacts to archaeological sites according to the type of impact incurred, HRV rating, the timing of impact relative to initial site discovery, and degree of surface disturbance. Through comparison of the date of initial discovery with the date(s) of site impact, we further split sites into four categories (Table 3):

1) Disturbed before site discovery,

2) Disturbed before and after site discovery,

3) Disturbed after site discovery, and

4) Undisturbed (Table 3).

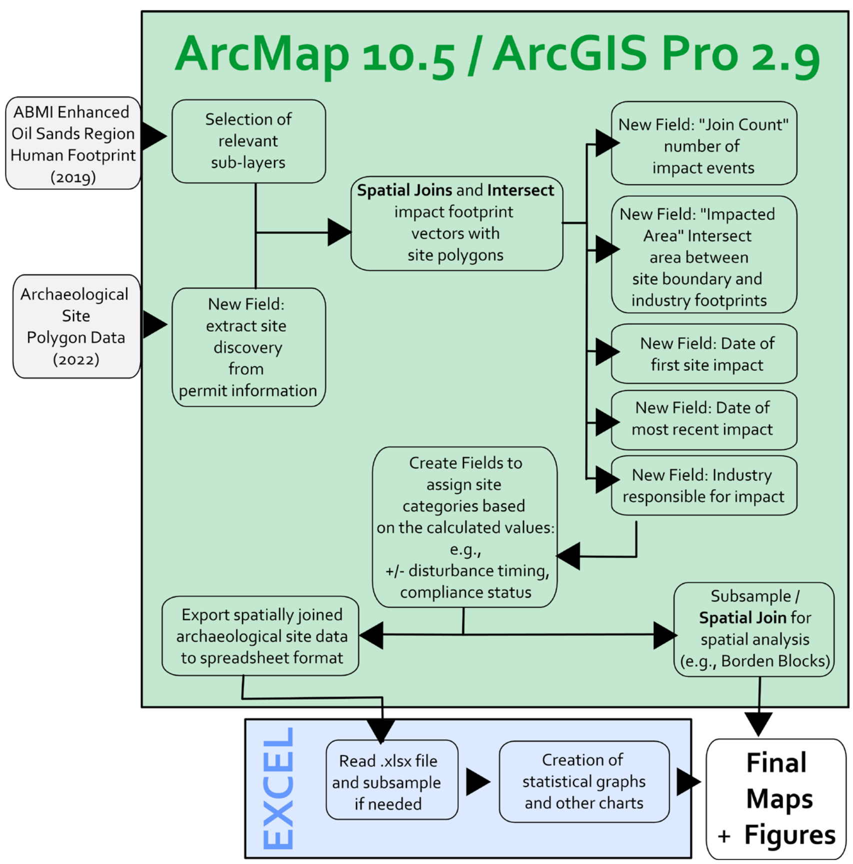


Figure 2. Impact analysis methods visually summarized. The names of specific tools are in bold.

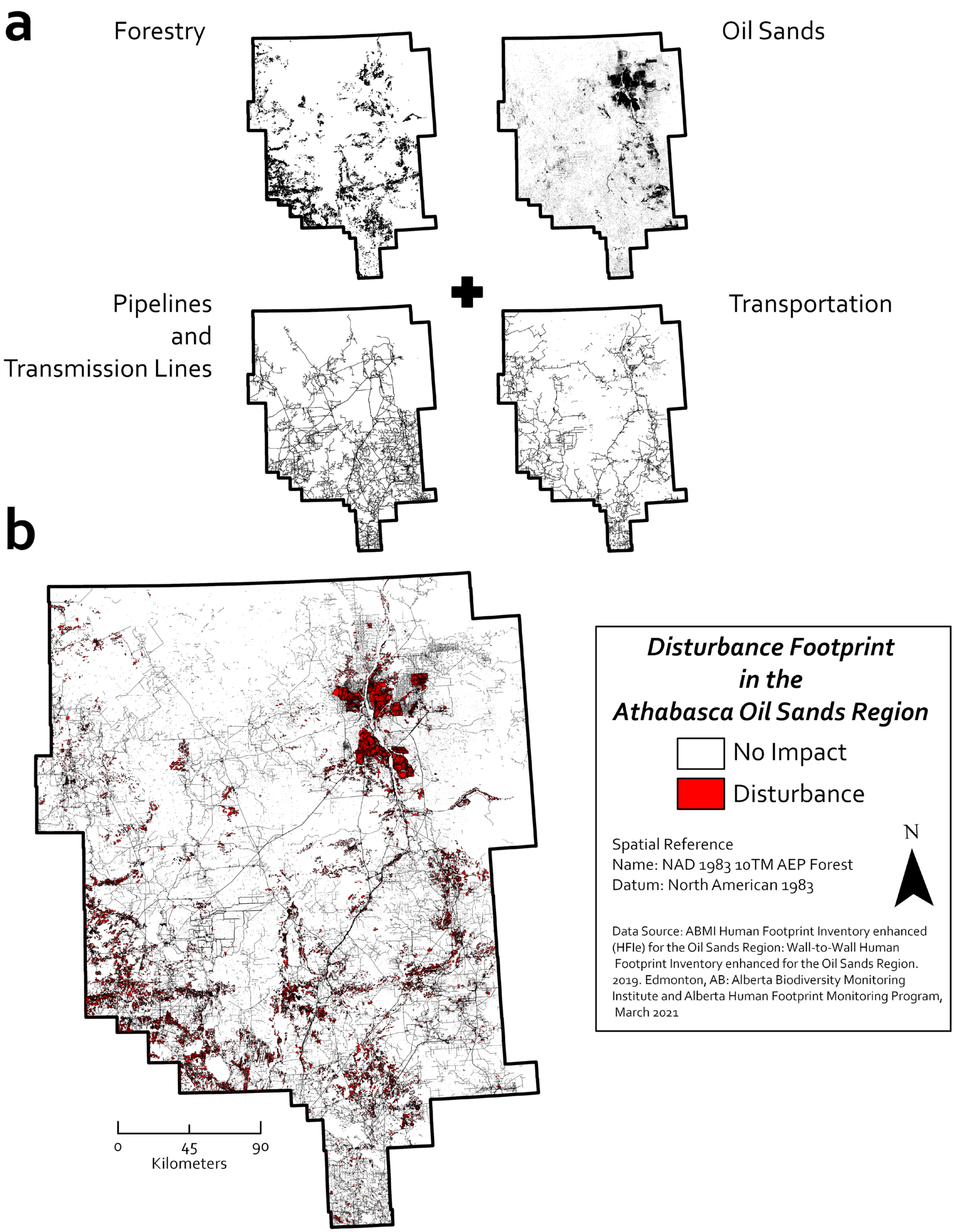


Figure 3. Conceptual map visualizing impact / disturbance in the Athabasca Oil Sands. a) Forestry, oil sands, pipeline, transmission lines, and transportation disturbance footprints are shown being added together. This does not represent all the sublayers used in the analysis. b) A summary view of human disturbance created using ABMI's (2021) Human Footprint Inventory enhanced (HFIe) for the Oil Sands Region.

Table 3. Impact categories used in this study.

Disturbance timing	HRV rating			
	HRV 1	HRV 3	HRV 4	HRV 0
Undisturbed	*HRA* compliant			
Before site discovery	*HRA* compliant			
Before and after site discovery	*HRA* non-compliant			*HRA* compliant
After site discovery	*HRA* non-compliant			*HRA* compliant

Sites that have HRV 1, 3 or 4 ratings that fall into Categories 2 or 3 are deemed potentially *HRA* non-compliant impacts because they were impacted after they received some form of protection in the HRV system. Impacts that were incurred to HRV 1, 3, or 4 solely prior to initial site discovery are categorized as *HRA*-compliant. Although these sites are disturbed, enough remained intact at the time of first recording to warrant non-HRV 0 status and no subsequent impacts have occurred. All impacts to HRV 0 sites are considered *HRA*-compliant. We also compiled summary statistics on the percent area of surface disturbance to sites and the industry types responsible for site impacts.

As a final note, different data analysis methods were attempted over the course of this research project. These included converting the vector impact footprints to raster data and the inclusion of pre-2000 archaeological sites. The methods and results presented here represent the most logical and methodologically accessible of those we attempted. Although this paper constrained the dataset/methods, the larger datasets and different methods employed also generated very similar results. Similarly, the methods work well in both ArcMap 10.5 and in the newer ArcGIS Pro 2.9, but only one version of the software is required. This iterative testing both builds confidence in our methods and the following results and should encourage other researchers to develop their own methods using similar datasets.

5. Results

5.1 HRV rating and HRA compliance status

Of 1,984 pre-contact archaeological sites in the AOS, 844 (43%) have been disturbed (Table 4). A total of 621 impacted sites are rated as HRV 0. This represents 31% of all sites (n=1984) in the AOS and 73% of disturbed sites (n=844). Disturbed HRV 4 sites (n=220) account for 11.1% of all sites and 26.1% of disturbed sites. Seven HRV 1 sites have been disturbed. This accounts for 0.3 % of all sites and about 0.8% of disturbed sites. Potential *HRA* non-compliant impacts affected 160 sites, which is 8.1% of all sites and 19.0% of disturbed sites. These 160 sites with potential *HRA* non-compliant impacts represent 21.2% of all non-HRV 0 sites (n=756), including five HRV 1 sites and 156 HRV 4 sites.

Table 4. Impacts relative to HRV rating and *HRA* compliance status. Shaded cells indicate potential *HRA* non-compliant impacts (n=160).

Pre-contact site disturbance status (n=1985)					
Disturbance timing	**HRV rating**				**Total**
	HRV 1	HRV 3	HRV 4	HRV 0	
Before site discovery	2	0	65	136	203
Before and after site discovery	2	0	16	84	102
After site discovery	3	0	139	401	543
Subtotal disturbed Sites	7	0	220	621	848
Subtotal undisturbed sites	12	4	517	603	1136
Total	**19**	**4**	**737**	**1224**	**1984**

5.2 Impact timing, frequency, and severity

Across the full sample, most sites (64.1%) were impacted after discovery (Table 4), the average number of impact events per site is 3.7, and the average surface disturbance for all HRVs is 43.8% (Table 5). Impacts to HRV 1 and HRV 4 sites in the *HRA* non-compliant sample tend to be more frequent (higher number of impacts) but less extensive (but still significant) in surface area. HRV 0 sites tend to be impacted less frequently but are also more extensively disturbed than non-HRV 0 sites (Figure 4). A total of 74 sites that should be protected have less than half of the site area intact.

Table 5. Average number of impact events and average % surface disturbance for all sites and potential *HRA* non-compliant impacts.

	All sites		***HRA* non-compliant**	
HRV	Average number of impacts	Average % surface disturbance	Average number of impacts	Average % surface disturbance
HRV 0	1.9	72.9	-	-
HRV 1	6.0	11.5	8	15.0
HRV 4	3.3	47.1	4	52.5
All HRVs	3.7	43.8	-	-

5.3 Industry sectors responsible for impacts

A total of 1,751 disturbance events have impacted 848 archaeological sites in the AOS (compliant and non-compliant). Oil Sands surface mining and other bitumen extraction developments account for a slim majority (n=896, 51.2%) of these impact events (n=1751), with transportation (n=471, 27%) and forestry (n=276, 15.5%) also heavily contributing to site disturbance (Tables 6 and 7). Bitumen surface mining accounts for, on average, the greatest extent of disturbance to archaeological sites (81.8%). Average disturbance to archaeological sites from forestry (65.1%) and other forms of oil sands mining / oil and gas (~50%) were also high.

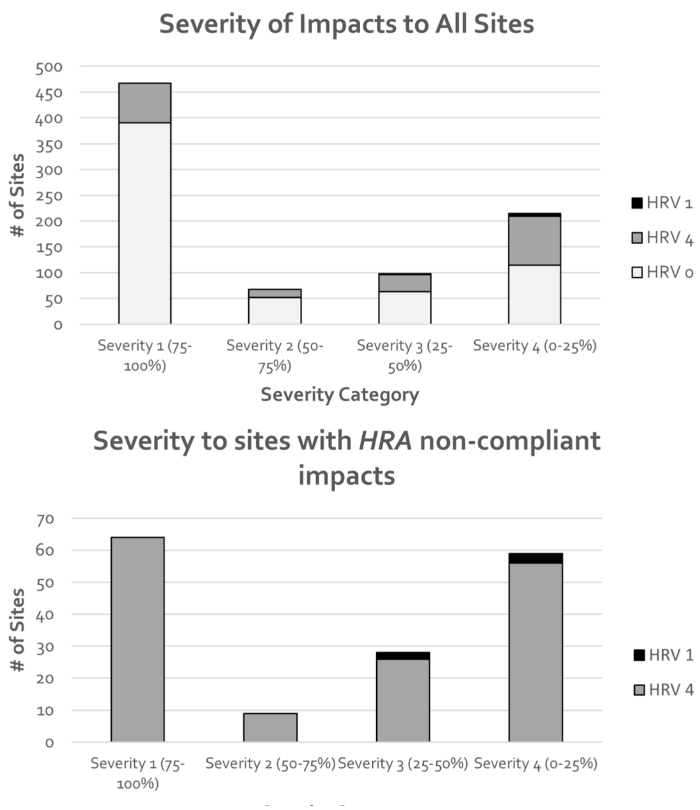


Figure 4. Top) Summary of impact severity based on percent area disturbance (*HRA* compliant and *HRA* non-compliant impacts). Bottom) Summary of impact severity based on percent area disturbance (*HRA* non-compliant impacts).

Based on our analysis, a total of 606 potentially *HRA* non-compliant impact events have occurred at 160 sites. The majority of these non-compliant events (n=606) are attributable to transportation developments (n=338, 55.8%). The next most common *HRA* non-compliant events are related to forestry (n=119, 19.6%) and the various bitumen extraction activities (n=103, 17.0%).

5.4 Geospatial patterns

When examined across the AOS region, impacts to archaeological sites are most severe outside of the surface mineable region around Fort MacKay (Figure 5). We normalized the amount of site disturbance (%) per disturbed site and number of *HRA* non-compliant impacted sites by total number of sites discovered in the minor Borden block (n=3250 across the AOS region as of January 2022). While this highly developed area still contains impacted sites, particular hot spots for both metrics were to the south-west and west of the region. The most impacted areas based on average % disturbed and number of *HRA* non-compliant impacts are minor Borden blocks toward Slave Lake and along the Athabasca River. Sample sizes are much lower in these Borden blocks compared to the surface mineable oil sands region, and as such, there is uncertainty in some of these values. That being said, an interesting trend to be investigated further is that both metrics suggest that more isolated archaeological sites (in relation to number of sites within the Borden block) are also more prone to both compliant and non-compliant impacts.

Table 6. All impact events summarized by ABMI industry sector. Average impact by industry to individual archaeological sites is also shown (averages were not calculated for samples under 30).

Industry sector	HRV			Total impact events	Average % site disturbance
	HRV 0	HRV 1	HRV 4		
Bitumen - surface mining	606	15	50	663	81.8
Bitumen - *in situ*	51	0	40	91	57.6
Energy transmission	3	0	2	5	-
Forestry	138	0	138	276	65.1
Other - surface mining	1	0	0	1	-
Municipal industrial	3	0	2	5	-
Municipal residential	1	0	0	1	-
Oil & gas - bitumen - unknown	103	5	34	142	17.8
Oil & gas - conventional	31	0	47	78	48.4
Recreational	0	0	2	2	-
Transportation - major	68	9	273	350	58.2
Transportation - minor	43	2	76	121	69.1
Unknown	5	0	3	8	-
Total	**1,053**	**31**	**667**	**1,751**	

Table 7. *HRA* non-compliant impact events summarized by ABMI industry sector.

Industry sector	HRV		Total number of impact events
	HRV 1	HRV 4	
Bitumen - surface mining	15	40	55
Bitumen - *in situ*	0	36	36
Energy transmission	0	1	1
Forestry	0	119	119
Municipal industrial	0	1	1
Oil & gas - bitumen - unknown	3	9	12
Oil & gas - conventional	0	41	41
Transportation - major	9	257	266
Transportation - minor	2	70	72
Unknown	0	3	3
Total	**29**	**577**	**606**

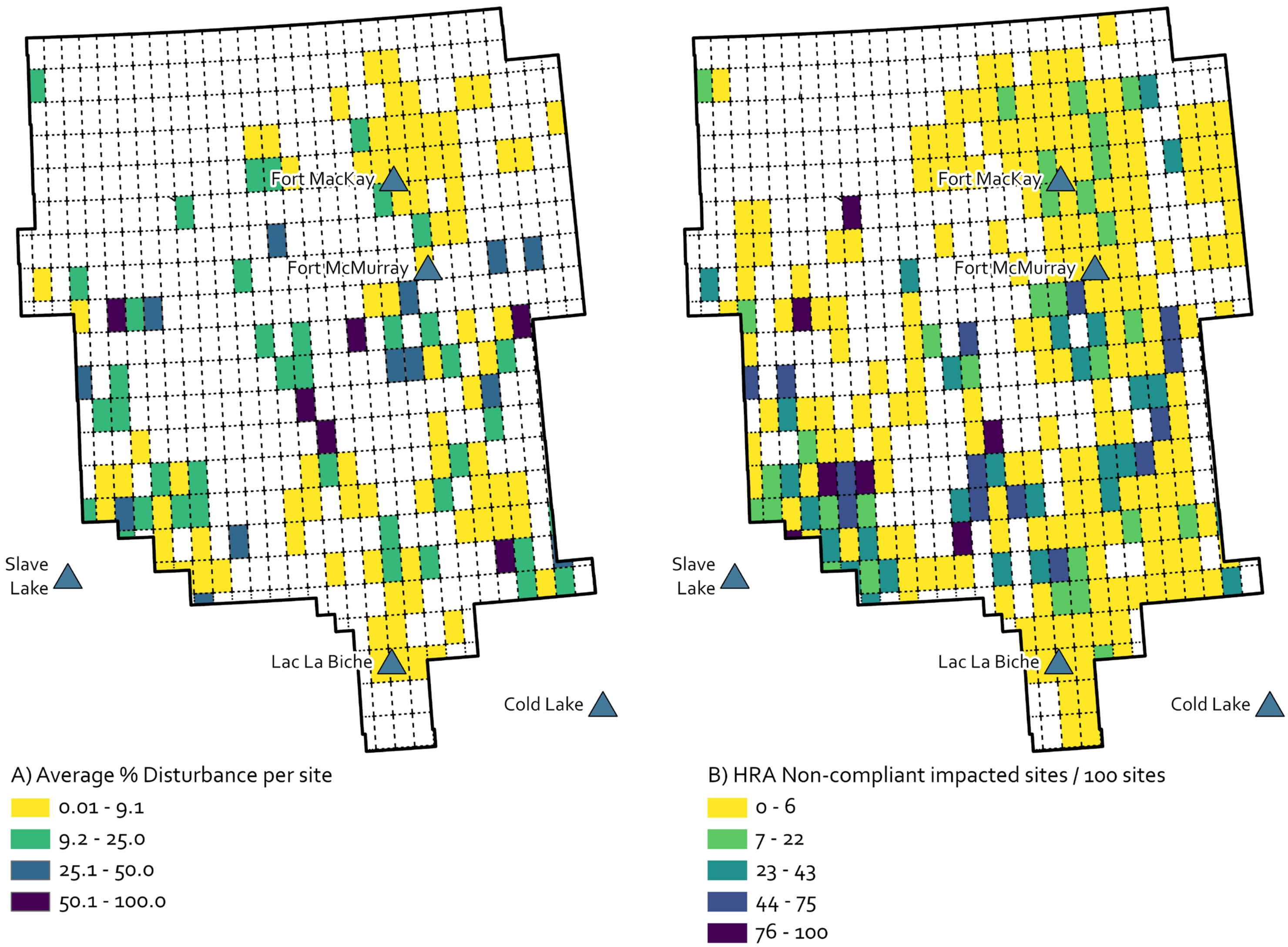


Figure 5. Geospatial patterns of select impact results. A) Average percent disturbance of impacted archaeological sites within a minor Borden block, normalized based on all sites discovered in minor Borden block (as of January, 2022, n=3250). B) Number of potential *HRA* non-compliant impacted sites per every 100 sites discovered (normalized by all sites discovered in minor Borden block).

6. Discussion

Using GIS and remote sensing to monitor archaeological sites in Canada is not a new premise, nor does this study represent the first-time similar strategies have been applied in Boreal Forest archaeology. In fact, the first significant attempts of using GIS and predictive modelling to locate and manage archaeological sites were undertaken in the Boreal Forest (i.e., the CARP project; Hamilton 2000; Ebert 2004). In the early 1990s, Dr. Scott Hamilton and his colleagues at Lakehead University recognized the high impact of industrial development on archaeological sites in the southern boreal forest and that contemporary CRM strategies were inadequate at preventing this destruction. Twenty years later, the regulatory framework associated with Boreal Forest archaeology has matured in Alberta. However, consistent monitoring of site impacts remains a gap in the system. Access to new and emerging satellite remote sensing datasets and increasingly capable GIS systems have given us a new suite of tools that make better monitoring practices possible.

Our study presents a 'snapshot' of disturbance levels to pre-contact archaeological sites (discovered between 2000-2019) in the AOS. Most sites remain undisturbed or were impacted under *HRA* approvals. However, our results indicate that 8% (n=160) of the total number of pre-contact sites (n=1,984) in the AOS have been potentially disturbed by *HRA* non-compliant impacts (Table 4). This represents 21% (160/760) of all pre-contact sites that are rated HRV 1, 3, or 4 and should be protected from impact. The average degree of surface disturbance to all sites is 43% and average number of impacts is 3.7 events. Therefore, impacted archaeological sites are not impacted just once, but multiple times, and to a significant extent. The impacts to archaeological sites were spread across multiple industries, with the majority being in transportation, forestry, and oil sands surface mining. Our results suggest impact patterns vary by industry. It is important to note that these values are maximum estimates. Several factors introduce uncertainty into our analysis that may inflate impact metrics. These factors are discussed below.

6.1 Interrogating compliance

We recognize that the current state of archaeological GIS data gathered by the ASA limits our ability to conclusively determine which of our 227 disturbed sites (impacted before, during, and after discovery in Table 4) have been subject to mitigative studies, and thus were compliantly impacted. This is because there is a large quantity of tabular data from excavations and other HRIM information that is not connected to the database in a useable way. Interested in knowing whether we could more conclusively determine which of these sites were *HRA* non-compliant, we requested this tabular data from the ASA and manually compared the methods used on site and timing of mitigation to our GIS results.

We found that the overwhelming majority of sites in our disturbed site sample (n=227) were not subject to HRIM excavation. Only 39 disturbed sites (17.2%) were excavated and the remaining 82.8% (188) were investigated by shovel tests or surface identifications alone. Of the 39 sites, 18 were likely compliant impacts that triggered excavation, six were impacted prior to the site being discovered (and therefore not protected under *HRA*), one was impacted prior to establishment of *HRA*, seven were originally impacted prior to excavation (likely non-compliant) but were later mitigated, and finally, seven protected/known sites were impacted by *HRA* non-compliant impacts prior to mitigative excavation. For the 188 unexcavated sites, the current data cannot provide a clear answer of whether or not these sites were investigated to the degree that the *HRA* warrants prior to impact. As such, impacts on these sites are considered potentially *HRA* non-compliant. This situation is more alarming when the potential severity of impacts to archaeological sites is considered in comparison to investigation methods (Figure 6). Both excavated and unexcavated sites are well represented in each of the severity categories (ranging from overlaps of 0-100%). This suggests there is no clear correlation as to whether excavation increases or decreases the severity of site impacts. As a result, we propose that the majority of unexcavated sites are potentially *HRA* non-compliant and perhaps severe. In order to be more precise with our results, however, the current ASA GIS databases would have to be improved to compare across fields and replicate the manual comparisons presented here more easily. We discuss the variables that would need to be improved in order to accelerate impact analysis more specifically below.

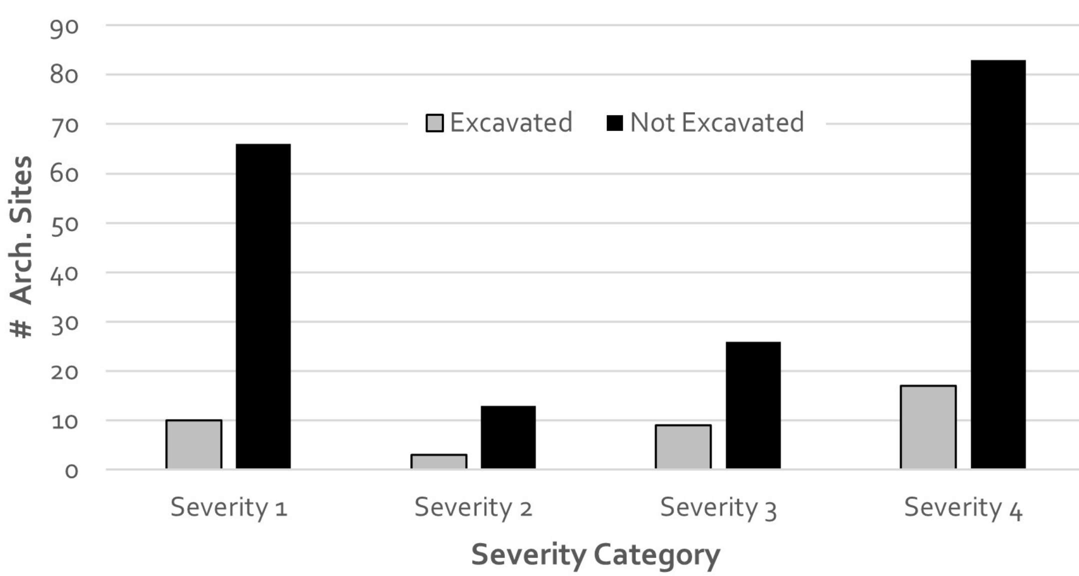


Figure 6. A graph comparing scientific methods to severity of impacts to archaeological sites. Excavated sites were examined in text for their *HRA* compliance status, however, the vast majority of sites remain unexcavated and thus we have limited knowledge of whether or not these impacts were mitigated. Between these two samples, all severity categories are represented.

6.2 Tracking changes with Historic Resource Values

Archaeological site data are provided to users as a flat database or "snapshot" of site attributes at the time of request. The dataset is subject to frequent internal updates, and the recording of HRV changes in the database can be delayed for various regulatory reasons (e.g., delinquent reports). Due to the fact that HRV rating updates are not "live," it is possible that some sites in our analysis with non-HRV 0 ratings are actually HRV 0 in the Government of Alberta system. These delays may be years in length for extremely delinquent reports, but most of this error is likely restricted to the year most recent to the data acquisition date. We cut off our site data in 2019 and assume that inaccuracies associated with these delays are relatively limited. However, this cannot be confirmed using available data.

Another aspect influencing our results is the spatial assignment of HRVs to sites. Currently, only one HRV is associated with each site even though impacts to select portions of non-HRV 0 sites can be approved. An example of this is HhOv-304 (Figure 7). This site straddles the designated area (i.e., HRV 1 land) associated with the Quarry of the Ancestors site complex. Only the portion within the designated area is protected from impact; the portion outside this boundary was subject to mitigation studies related to the East Athabasca Highway and development proceeded within the non-designated portion of the site. This site, therefore, has two functional HRVs; 0 for the non-designated area and 1 for the designated area. However, the site retains only its highest (HRV 1) in the site database. We suspect similar regulatory complexities have affected all of the non-compliant impacts to HRV 1 sites in our analysis because they all occur adjacent to the Quarry of the Ancestors. We term these multiple intrasite ratings as "compound HRVs." To filter out the true HRV rating for a site, one would need to review site forms, reports, and other regulatory applications approved for different areas within a site that recommend HRV values to the government. These are not available within the current GIS database (as seen in section 6.1) and represent one of the limitations of this study. If such data were incorporated into the official ASA database this would greatly improve cumulative effects assessments and data utility.

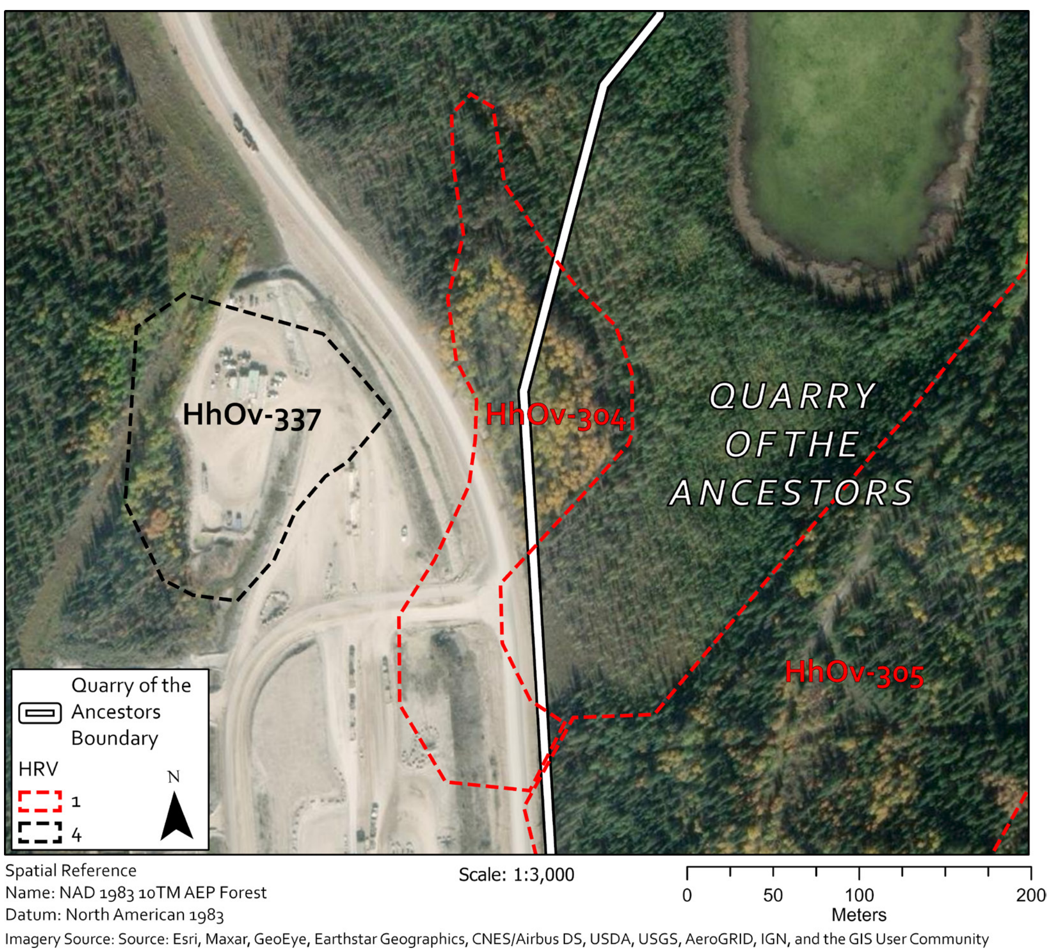


Figure 7. An example of the "compound HRV" problem in this dataset. Seen in this satellite imagery, the East Athabasca Highway was constructed along the boundary of a significant site group (Quarry of the Ancestors) and disturbed an HRV 4 site (HhOv-337) and a portion of an HRV 1 site (HhOv-304). Although the portions of HhOv-304 that fall within the boundary are protected, those outside were allowed to be impacted. This represents a discrepancy in how HRV values are applied across a site.

Complications arising from delayed HRV status updates and the occurrence of compound HRVs cannot be quantified without access to internal government data. We assume issues are fairly uncommon because several factors need to synchronize to introduce an error (e.g., HhOv-304). Regardless, these errors can create significant misconceptions about the impact status of protected sites. These misconceptions can be avoided by providing more detailed spatiotemporal tracking data of HRV changes in the government archaeological site database.

6.3 Trouble with polygons

Similar to the issues faced with HRV data, other site variables were also explored in the hopes these may also contribute to our analysis. Specifically, the permit, site type, and cultural affiliation data fields were explored but ultimately deemed too complicated to incorporate. Opposite to the HRV problem, each row in these fields contains multiple variables forcing sites to straddle multiple categories and other technical issues. Although these challenges are not insurmountable, a significant amount of analysis time/labour would be needed to include these variables. Tabulating the permit category into a 'count' of permits issued per site would also be useful to compare to the impact results as an analogue for site re-visits or (perhaps) mitigative work without the need to sift through countless site forms and non-GIS data (previously mentioned in section 6.1). Similarly, site type and cultural affiliation may help disentangle which sites (e.g., less visible or older sites) are being impacted and help to focus monitoring strategies.

Site size, calculated in ArcGIS from administrative polygon boundaries, also proved to be difficult to incorporate. Although an effective analogue for calculating percent area disturbance, when used in correlation analysis, the overabundance of two specific site sizes skewed the statistics. Over 1200 sites have an area of exactly 900 square metres, and over 500 have an area of around 3600 square metres. Both of these categories represent perfectly square administrative boundaries and appear to be a standard geospatial tool applied. This uniformity relates to the default sizes associated with sites previously digitized from NTS map points. Although there is some uncertainty about these administrative boundaries, for lack of a substitute, we accepted the limitation. With the advent of collecting spatial data from consultants (2014), site polygons are now more representative of archaeologist-delineated site boundaries.

The ABMI dataset was incredibly useful and we found only one limitation with the disturbance footprint polygons. Specifically, the transportation vector data are more split up than other industries (e.g., forestry, oil sands mining) and may inflate the number of impact events. Upon examining the transportation data, multiple vectors often appear at intersections or road expansions (which are multiple impact events), and the majority of vector lengths appear longer than archaeological sites. As a result, this inflation of impact event count is likely slight, but better than missing impacts from road expansions or renewals (which would require an HRIA if they were going to impact an HRV protected site).

6.4 Site management and monitoring recommendations

Through our analysis we can contextualize the current site monitoring situation for archaeological sites in the AOS. We have demonstrated that it is possible to potentially identify the type (compliant or non-compliant), extent, and severity of site impacts, as well as the industry sectors that disturb archaeological sites using GIS / remote sensing strategies. Although we have drawn attention to current challenges facing the ASA and the CRM industry, this analysis has shown that the majority of archaeological sites are protected by the current system. However, a substantial proportion of sites are still impacted, and there is clearly opportunity for improvement. If not improved, every percent lost of a site may remove evidence that could firmly establish it within a chronological period, link it to an archaeological culture, or change its present meaning to modern people. The high chance of losing this crucial evidence on a massive multi-site scale is why better practices are needed now.

We recognize that Alberta is a vast district to regulate, and methods to monitor site impacts have not been incorporated in the past due to data availability and technological limitations. In this study, we present improved and accessible resources making better site monitoring possible. In Figure 5, we show how such tools can be used to derive information about particular regions within AOS that may require heightened monitoring/management. In Figure 7, we show that similar techniques can be used to monitor specific sites under threat. A key task going forward is to leverage better site monitoring methods in the practice of CRM. To this end, efforts should be made to: 1) incorporate regular remote sensing / GIS assessments of non-compliant site impacts into the regulatory process, and 2) ground-truth and evaluate impacted sites identified through site monitoring analysis. We suggest that a standardized GIS site impact analysis routine similar to the one we present here be adopted by the ASA and published at regular intervals, perhaps in sync with the release of the Listing of Historic Resources.

In terms of ground-truthing impacts, we recognize that the labour pool of archaeologists in Alberta is likely far too small to monitor all effects, past and present, and as a result we propose a different solution. In-field monitoring is critical to ensure that management systems are working as predicted. Such ground-truthing / monitoring of industry impacts may be achieved through Indigenous community-based monitoring already active within the Oil Sands Monitoring Program in Alberta. Incorporating archaeological sites into such a program would both improve site monitoring strategies by increasing site revisit data (one of the aforementioned avenues the ASA uses to understand site impacts) and provide an opportunity for Indigenous peoples to connect with their ancestral places and promote archaeological education. Similarly, it would also contribute to the development of impact severity indexes (e.g., CRICS; Gibson 2019 [2005]) through increasing the sample size and evaluation of different industry "footprints" and their disturbance of archaeological sites. To this end, we encourage and support efforts to work with Indigenous communities to build their capacity in historic resources management and determine triggers for when removal of historical resources infringes on Section 35 rights under the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP). As stated in Article 11 (2007:5):

> "Indigenous peoples have the right to practise and revitalize their cultural traditions and customs. This includes the right to maintain, protect and develop the past, present and future manifestations of their cultures, such as archaeological and historical sites, artefacts, designs, ceremonies, technologies and visual and performing arts and literature."

We suggest collaborative partnerships between Indigenous communities, post-secondary institutions, and CRM professionals to develop such programs. Such work will result in improved management of archaeological sites and landscapes from both cultural and scientific perspectives.

As a final note, it is important to briefly raise the fact that all of the challenges presented here for site monitoring in Alberta will soon be exacerbated by anthropogenic climate change (Rockström et al. 2009; Nenzén et al. 2019). While much of archaeological efforts are rightly focused on rising sea levels and shoreline erosion threatening coastal sites (e.g., Anderson et al. 2017; O'Rourke 2017), Canadian archaeologists have been less focused on climate change impacts to interior Canada. The same methods used in this paper to monitor industry impacts can also be leveraged to monitor climate change effects that effect interior sites, such as increased wildfire frequency and extent. As concerned archaeologists, it is our plea that we begin to monitor all impacts to archaeological sites before they are gone.

7. Conclusion

Northeastern Alberta has been a well populated and storied landscape for thousands of years (Ives 1993), but in the last hundred years significant portions of this region's history have been removed from the land by industry. This study provides the first quantitative analysis of these impacts by using publicly accessible satellite remote sensing products. We present simple methods that could be incorporated into site management practice. Twenty percent of pre-contact sites slated to be protected from impact in our sample were found to be disturbed as a result of potentially *HRA* non-compliant industry activities. With these added tools, and leveraging existing Indigenous community monitoring programs, management and monitoring strategies may improve and change the fate of many sites. We believe these strategies must be put in place now to prevent greater destruction of archaeological sites. The need to protect these non-renewable resources will increase if industrial activities escalate and continue to threaten these resources.

8. Acknowledgements

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9. Data availability statement

The disturbance/impact data was obtained from the public Human Footprint dataset (2021) produced by the Alberta Biodiversity Monitoring Institute (available here: https://www.abmi.ca/home/data-analytics/da-top/da-product-overview/Human-Footprint-Products.html). To obtain the archaeological site data used in our analysis please contact the Archaeological Survey of Alberta. Unless otherwise cited in figure captions, all other geospatial data used to create maps or figures were freely obtained under the Open Government License-Canada and can be accessed online (from http://geogratis.cgdi.gc.ca/).

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